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Forensic Expertise in Determining Damage to Plant Life Caused During Armed Conflicts: Legal Brief on the Case of the Russian-Ukrainian War

Volodymyr Yusupov[1], Hubenko Ivan[2], Nataliia Kisil*[3], Kateryna Yusupova[4], Olena Cherniavska[5]

[1]National Academy of Internal Affairs, Kyiv, Ukraine. Email: yusupov.v@gmail.com
ORCID: https://orcid.org/0000-0001-5216-4144
[2]National Academy of Internal Affairs, Kyiv, Ukraine. Email: ivanhubenko@gmail.com
ORCID: https://orcid.org/0009-0006-8137-4638
[3]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine. Email: kisil_n@ukr.net | ORCID: https://orcid.org/0000-0003-1097-360X
[4]National Academy of Internal Affairs, Kyiv, Ukraine. Email: yusupovakaterina@gmail.com
ORCID: https://orcid.org/0000-0002-8508-3516
[5]Kyiv Scientific Research Institute of Forensic Expertise, Kyiv, Ukraine.
Email: olena.pr@ukr.net | ORCID: https://orcid.org/0009-0008-4619-5399
Corresponding author

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Abstract

This article explores the types of forensic expertise used for assessing environmental damage, particularly to plant life, and in the context of armed conflicts. This study considers documented ecological damages from the Russian-Ukrainian war and Ukraine's practical experience following the combat activities of the Russian Federation in assessing damage to plant life. The research was based on forensic doctrines related to crime trace collection, aimed at better understanding the current mechanisms used for documenting environmental damage caused by armed conflicts, as well as exploring general forensic theory, which analyses types of forensic processes used to determine environmental damage resulting from warfare. The study analysed statistical data provided by Ukraine's Prosecutor General's Office concerning environmental war crimes from 2022 to 2024, quantitative indicators of environmental damages from governmental audit reports, and included a mathematical calculation of ecological damages caused by a specific event in September 2024 - following the debris fall of a shot-down Kh-59/69 missile in Kyiv region (Ukraine). Findings from the forensic assessment of environmental harm derived from armed conflicts are accepted by international courts as evidence of war-related environmental crimes. The mathematical calculation proposed in this article for determining the magnitude of environmental damage can be employed by specialists developing methodologies for conducting relevant forensic expertise. The study empirically substantiates the potential of forensic methods for quantifying environmental damage caused to ecosystems and plant life as a result of military operations.

Keywords

Forensic expertise; Special knowledge; War crimes investigation; Ecological damage; Plant varieties; Assessment of damage to plant life

Introduction

The right to a safe environment is a fundamental human right. Various armed conflicts and local wars occurring in the 21st century significantly harm the natural environment. Global challenges to ecological stability are further exacerbated by negative impacts such as atmospheric pollution, soil contamination, destruction of protected natural territories, devastation of flora and fauna, depletion of mineral resources, ammunition explosions, missile and bomb strikes, and the use of hazardous toxic substances. Following February 24, 2022, when the Russian Federation initiated a full-scale military invasion of Ukraine, the climate crisis deepened significantly, as approximately 40% of Ukraine's land became contaminated by various types of ammunition. Combat actions continue to inflict substantial damage to the ecology of the region, resulting in additional greenhouse gas emissions into the atmosphere. This pattern of widespread ecological harm has also been observed by other researchers (Rawtani *et al.,* 2022). In the first seven months of the Russian-Ukrainian war, greenhouse gas emissions amounted to a minimum of 100 million tons of CO_2, equivalent to the annual emissions of a country like Belgium. As many adverse effects of this war remain unaccounted for, these figures likely underestimate actual emissions (Bun *et al.,* 2024; Klerk *et al.,* 2022). This negative environmental impact is likely to persist for years. Since environmental effects cross borders, the consequences of the war in Ukraine will extend beyond its territory and have a global impact.

Documented instances of Russian war crimes against Ukraine, notably environmental damage, must be addressed in the International Criminal Court (ICC). Accurate documentation and evidence collection are critical for establishing liability for the damages caused by the war. Judicial expertise and expert conclusions are also crucial procedural measures as they adhere to principles of objectivity, independence, scientific validity, verifiability, and international standards compliance Firstly, judicial expertise provides expert conclusions from researching negatively impacted environments by armed conflict; these environments and what they contain, such as flora and fauna, are permanently preserved as material evidence by investigative authorities. Expert opinions serve as admissible evidence in international proceedings to hold individuals and states accountable for war-related damages. Secondly, experts, based on their practice, may propose measures to prevent or mitigate the harmful impact of specifically damaging military operations. Thirdly, Ukraine's experience in environmental protection and restoration following more than three years of damage from the Russian Federation will serve as a valuable model for other countries facing similar military conflicts, helping formulate effective future preventive measures.

In the past five years, the global scientific community has intensified research into environmental threats arising from 21st-century military conflicts involving various weapons and their ecological impacts. Scholars have focused on the international criminalisation of "ecocide", forecasting the negative impacts of war-related pollutants, and developing preventive measures to mitigate climate threats to humanity. Specifically, Hashmatulla (2023) argued that criminal liability for environmental crimes remains controversial and not fully recognised by the international community. The Rome Statute regulates international criminal responsibility for environmental crimes only in conjunction with war crimes. Establishing effective international standards and

collaborative strategies can create a more cohesive and efficient system for environmental protection. Voigt (2021) advocated for the legal definition of "ecocide", proposing amendments to the International Criminal Court (2011) to include it as a fifth international crime, that, according to Stasiuk (2024), could contribute to the creation of an international tribunal for environmental crimes, which would specialise in liability for environmental damage caused during armed conflicts.

Several researchers analysed the negative environmental consequences of armed conflicts. It is emphasised that Ukraine is uniting the world by developing an effective strategy for holding individuals accountable for war crimes against the environment, thus creating a preventive precedent for the future. Damage assessment is highlighted as an essential initial stage in investigating environmental war crimes. Without proper assessment, national and international judicial institutions cannot accurately classify the impact of armed conflict on the environment (Zadykhaylo, Serputko and Kharlamova, 2023). Environmental crimes are now a key part of warfare and cause lasting damage to our natural resources, ecosystems, and public health. The war in Ukraine has resulted in many environmental disasters. Damage to things like oil refineries, chemical plants, power stations, and gas storage facilities releases harmful substances into the air, soil, and water. Additionally, operational monitoring and evidence collection during combat activities are challenging (Koroliova and Danyl, 2024). Prodan, Khomin and Andrushko (2023) noted that the impacts on forests, steppes, and water bodies in Ukraine will persist for decades, continuing to pose threats long after active hostilities cease. Heavy metals from ammunition and military equipment also contaminate soil and groundwater, and fires caused by bombardments destroy rare plant and animal species. Additionally, capturing and shelving nuclear power plants pose technogenic disaster risks not only to Ukraine but also to neighbouring countries. Ukraine has significant potential to become the first country globally to receive reparations for environmental crimes.

Panteleeva, Syvyi and Hanchuk (2023) emphasised the need for recording and documenting environmental damages during the Russian-Ukrainian war to build evidence for international independent commissions and judicial bodies. The development of forensic tools to counteract ecocide based on international and national experiences is explored by Petrova (2024). Shevchuk, Zatenatskyi and Matulienė (2024) highlighted forms of international cooperation with governmental and non-governmental entities in ecocide investigations. However, scholarly literature lacks sufficient attention regarding forensic examinations to determine environmental damages caused by military actions in armed conflicts and the role of forensic expertise in international mechanisms for prosecuting responsible individuals.

The primary objective of this article is to explore the role and methodologies of forensic expertise in assessing ecological damage, particularly to plant objects, caused by armed conflicts. Using the Russian-Ukrainian war as a case study, the article develops and applies a quantitative framework for calculating environmental damage, aiming to support evidence-based war crime investigations.

Materials and Methods

This article employs a combination of general theoretical and specialised scientific research methods, which together substantiate the selected research topic. In alignment with the defined objectives and tasks, synthesis and theoretical analysis methods were applied, supported by a review of scientific literature on forensic expertise concerning the destruction or damage of plant life, particularly as a consequence of armed conflicts. The functional method was employed to investigate the mechanisms for assessing environmental damage resulting from combat activities during the Russian-Ukrainian war. An analytical approach facilitated the exploration and development of a framework for quantifying the damage to plant life caused by war crimes. A systemic approach helped define the extent of the issue and guided the formulation of proposed solutions. The initial phase of the research involved gathering pertinent materials and statistical data on the environmental damage inflicted by the actions of the Russian military in Ukraine. Mathematical methods were utilized to calculate the extent of damage resulting from unregulated emissions of pollutants or pollutant mixtures into the atmosphere, drawing on specific documented instances of ecological harm during the conflict.

To test the developed forensic methodology for assessing environmental damage, secondary data was used, specifically information on the area and duration of a forest fire caused by missile debris during a combined Russian air attack in 2024 in the Vyshedubechanska community of Kyiv region, Ukraine. This data was provided by the State Enterprise "Forests of Ukraine" (DP "Lisy Ukrainy"). According to this data, on September 30, 2024, fragments from a downed guided aviation missile X-59/69 ignited dry grass, causing a forest fire. A total of 7 fires covering an area of one hectare were localised (Censor.Net, 2024). The development of the methodology for calculating damages required a study of existing guidelines for calculating environmental damages. These included several documents developed by experts from Ukraine's Ministry of Environmental Protection and Natural Resources and the State Ecological Inspection. This study draws upon several official methodologies adopted by the Ministry of Environmental Protection and Natural Resources of Ukraine for the assessment of environmental damage under conditions of armed conflict and martial law. These include:

- the *Methodology for Assessing Damage to Land and Soil Resulting from Emergency Situations and/or Armed Aggression under Martial Law* (Order No. 167, 2022)[1];
- the *Methodology for Calculating Unorganised Pollutant Emissions into the Atmospheric Air during Emergency Situations and/or Martial Law and for Estimating the Resulting Environmental Damage* (Order No. 175, 2022)[2]; and

[1] Order of the Ministry of Environment and Natural Resources of Ukraine No. 167 (2022). Methodology for determining the amount of damage caused to land and soil as a result of emergency situations and/or armed aggression and hostilities during martial law of 04.04.2022. Official Gazette of Ukraine, 31: 2y07.

[2] Order of the Ministry of Environment and Natural Resources of Ukraine No. 175 (2022). Methodology for calculating fugitive emissions of pollutants or mixtures of such substances into the atmospheric air as a result of emergency situations and/or during martial law and determining the extent of damage caused of 13.04.2022. Official Gazette of Ukraine, 33:516.

- The *Methodology for Assessing Damage to Forest Resources Caused by Armed Aggression by the Russian Federation* (Order No. 414, 2022)[3].

Although these guidelines do not constitute a forensic methodology per se, their specialised methodological instruments, once appropriately adapted and validated, served as the foundation for the development of a forensic approach to assessing damage to air, land, soil, and plant life.

Forensic expertise is among the most reliable and effective means of gathering evidence for establishing factual data in various legal conflicts, including determining the extent of damage to plant life. Expert studies employ scientifically validated, practically proven, and officially approved methodologies and techniques, producing evidence suitable for use in both national and international judicial proceedings investigating war crimes. Conclusions from forensic expertise constitute critical evidence in establishing accountability for environmental war crimes and determining compensation.

Table 1: Steps in Conducting Forensic Environmental Expertise during Armed Conflicts

1. Detection of Ecological Incident
↓
2. Collection of Initial Data (e.g., satellite imagery, field inspections, witness reports)
↓
3. Identification of Affected Area and Plant Objects
↓
4. Application of Legal and Methodological Framework (e.g., Order No. 175)
↓
5. Calculation of Environmental Damage (using formula with coefficients)
↓
6. Preparation of Expert Conclusion (admissible in judicial proceedings)
↓
7. Submission of Expert Report to Prosecutorial or Judicial Bodies

In Ukraine, environmental impact assessments (ecological expertise) study the circumstances and organisational-technical reasons and consequences of anthropogenic impacts on environmental objects (Verkhovna Rada of Ukraine, 1998; Verkhovna Rada of Ukraine, 2017). Among the goals of this type of expertise is determining the circumstances related to environmental emergencies. However, neither the tasks nor the existing methodologies of ecological expertise currently include procedures for calculating material damages caused by military actions. Despite ecological expertise and its subdivisions ideally addressing these tasks, the current framework is insufficient. Thus, it is proposed that regulatory documents governing forensic expertise explicitly incorporate processes to establish factual details regarding environmental emergencies

[3] Order of the Ministry of Environment and Natural Resources of Ukraine No. 414 (2022). Methodology for determining damage and losses caused to the forest fund as a result of the armed aggression of the Russian Federation of 05.10.2022. Official Gazette of Ukraine, 87:164.

resulting from military actions. Previously, researchers Krainov and Sabadash (2024) recommended supplementing the "Scientific-Methodological Recommendations on Preparation and Appointment of Forensic Expertise and Expert Research" (Verkhovna Rada of Ukraine, 1998) with a preliminary list of issues addressed when conducting expert assessment of the environmental consequences of war.

A range of forensic expertise types may be commissioned to assess damages on plant life, including ecological, engineering-technical, land management, fire-technical, chemical, commodity, soil science, biological, veterinary, and historical-archaeological. In specific cases involving intellectual property rights, plant variety expertise may also be required. Depending on the specific type of expertise, initiators receive critical forensic information (evidence) regarding: a) sources of contamination or environmental pollution during environmental crimes; b) nature and scale of air, water, and soil pollution (physical-chemical characteristics and toxic levels); c) causes of diseases and deaths resulting from environmental crimes; d) scope of damage and negative anthropogenic impacts on ecosystems (consequences of ecocide or threats thereof); e) regional and territorial environmental protection levels (administrative units); f) substances, materials, compounds, and objects (lethal or weapons) used in committing environmental crimes, regulated by criminal and environmental legislation (radioactive, explosive, toxic, hazardous substances, etc.); g) traces related to environmental crimes, such as those from weapons, explosive devices, ammunition, and radioactive emissions absorbed by air; h) evidence of damage to fauna and flora, among other aspects. The absence of a specialised forensic methodology for calculating plant damage from military actions complicates evidence collection in criminal proceedings related to war crimes.

Calculation of environmental damage

Based on the analysis of scientific literature and the recommendations of leading researchers, a new methodology for assessing environmental damage was developed. This methodology was used to calculate damage from unorganised pollutant emissions into the atmosphere resulting from the forest fire triggered by a combined Russian aerial attack on September 30, 2024, in the Kyiv region, Ukraine (Censor.Net, 2024). The following formula was applied (see Table 1):

$$\mathrm{AoD} = \mathrm{MoUE} \times \mathrm{TR} \times \mathrm{HC} \times \mathrm{CI} \times \mathrm{CSE} \times \mathrm{CNE}\,, \qquad (1)$$

AoD – amount of damage, in the national currency – hryvnia (UAH); *MoUE* – mass of unorganised emissions of a pollutant or a mixture of such substances into the atmosphere as a result of military actions, in tons (t), *TR* – tax rate for unorganised emissions of pollutants or their mixtures into the air according to national legislation (in Ukraine, this is the Tax Code of Ukraine (Art. 243 of the Law of Ukraine No. 2755-VI (Verkhovna Rada of Ukraine , 2010), in UAH/t; *HC* – hazard class coefficient of pollutants or their mixtures, determined according to national methodological recommendations (in Ukraine, this is the National Methodology (Order of the Ministry of Environment and Natural Resources of Ukraine No. 175, 2022)[4], *CI* – coefficient of environmental impact

[4] Order of the Ministry of Environment and Natural Resources of Ukraine No. 175 (2022). Methodology for calculating fugitive emissions of pollutants or mixtures of such substances into the

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depending on the duration of the event, determined according to the National Methodology, *CSE* – coefficient depending on the scale of the event, determined according to the National Methodology; *CNE*– coefficient depending on the nature of the event's origin, determined according to the National Methodology. The values of the coefficients are presented in table 1.

Table 2: The values of the coefficients used in formula (1)

Coefficient indicating the hazard level of pollutants or pollutant mixtures (HC)		
List of Pollutants or Their Mixtures		*HC*
NOX	Nitrogen dioxide	3
NH3	Ammonia	2
Sox	Sulphur anhydride	3
CO2	Carbon dioxide	2
CO	Carbon monoxide	2
NMVOC	Non-methane volatile organic compounds (NMVOC)	2
PM10 + PM2,5 (Soot)	Solid particles (dust + soot)	3
Pb	Lead and its inorganic compounds (in terms of lead)	5
Cd	Cadmium oxide (in terms of cadmium)	5
Hg	Mercury oxide (in terms of mercury)	5
As	Arsenic, inorganic compounds (in terms of arsenic)	4
Cr	Hexavalent chromium (in terms of chromium trioxide)	5
Cu	Copper oxide (in terms of copper)	4
Ni	Nickel oxide (in terms of nickel)	4
Se	Selenium dioxide (in terms of selenium)	5
Zn	Zinc oxide (in terms of zinc)	3
Benzo(a)pyrene	Benzo(a)pyrene	5
Impact Factor Coefficient (CI)		
Duration of Events, hours	*CI*	
If the duration of events is not determined	3	
Up to 12	4	
From 12 to 24	5	
More than 24	6	
Scale Factor Coefficient (CSE)		
Scale of Event, tons or Hectares	*CSE*	
If not determined or up to 50	1.2	
From 50 to 150	2	
From 150 to 500	3	
From 500 to 1000	4	
From 1000	5	
Indicator of the Coefficient of the Nature of Event Origin (CNE)		

atmospheric air as a result of emergency situations and/or during martial law and determining the extent of damage caused of 13.04.2022. Official Gazette of Ukraine, 33:516.

Nature of Event Origin	*CNE*
Emergency	3
An emergency that led to the impossibility of the population living in such an area or facility, or conducting economic activities there	6
State of war	10

Source: developed by the authors

In formula (1), MoUE equals:

$$\text{MoUE} = qi \times S,$$

Where *qi* is the specific emission factor of a pollutant or pollutant mixture, determined according to the National Methodology (Order of the Ministry of Environment and Natural Resources of Ukraine No. 175, 2022), measured in tons per hectare (t/ha); *S* represents the area of burned forest and other vegetation, in hectares.

Results

Significance of the forensic expertise

Every war leads to atmospheric poisoning, water resource contamination, and destruction or damage to flora and fauna, potentially causing environmental disasters. Among the gravest ecological consequences of the Russian army's military actions in Ukraine are the destruction of the Kakhovka hydroelectric power station dam and the explosion at the Kurakhove reservoir, resulting in significant flooding; the seizure and nuclear disaster at the Zaporizhzhia Nuclear Power Plant; and the drone strike on the Chernobyl Nuclear Power Plant sarcophagus, potentially worsening radiation levels. UN Secretary-General António Guterres described the destruction of the Kakhovka dam as "a massive humanitarian, economic, and environmental catastrophe in Ukraine's Kherson region" (Guterres, 2023). The head of the International Atomic Energy Agency (IAEA), Grossi (2025), also expressed profound concern regarding the compromised integrity of the Chernobyl sarcophagus.

Due to the Russian-Ukrainian war, approximately 188,000 km² of soil is at risk of contamination. Combat zones include 393 nature reserves. Recent research highlights that the integrity of these areas has been severely compromised due to shelling, infrastructure destruction, and secondary ecological stress (Filho *et al.*, 2024). Recorded incidents include fires impacting 298,000 hectares of forests and 1,438,000 hectares of grasslands, along with the burning of oil and petroleum products, resulting in significant atmospheric pollution (Minyailo and Minyailo, 2024). Emissions from military actions include nitrogen oxides, carbon monoxide, non-methane volatile organic compounds, sulfur oxides, dust, lead, cadmium, mercury, arsenic, chromium, copper, nickel, selenium, zinc, dioxins, dibenzofurans, and benzopyrene, among others.

Ukrainian legislation on criminal liability, in addition to general war crimes, specifically addresses ecocide (Art. 441 of the Criminal Code) and destruction or damage to flora

(Art. 245 of the Criminal Code), among other offenses (Verkhovna Rada of Ukraine, 2001). An analysis of statistical data from Ukraine's Prosecutor General's Office shows that during the Russian invasion from 2022 to 2024, law enforcement initiated pre-trial investigations into 23 criminal offenses classified as ecocide and 72 cases of destruction or damage to flora. Our analysis demonstrates a clear increase in environmentally related criminal offenses (Office of the Attorney General, 2025).

The environmental damage inflicted by war is meticulously documented by authorised Ukrainian agencies, primarily the Ministry of Environmental Protection and Natural Resources. As of February 2025, environmental losses resulting from military actions reached UAH 3.526 trillion; 7,502 environmental war crimes were documented, including 1,622 incidents involving atmospheric damage and 2,912 related to land resources (EcoZagroza, 2025). According to data from the State Forest Resources Agency of Ukraine and environmental research organizations, forested areas affected by military operations predominantly include species such as pine (*Pinus sylvestris*), oak (*Quercus robur*), hornbeam (*Carpinus betulus*), birch (*Betula pendula*), and ash (*Fraxinus excelsior*). These forests are prevalent in Kyiv, Chernihiv, Kharkiv, and Zaporizhzhia regions, where active combat and missile strikes have occurred. Recent studies estimate that up to 18% of protected plantations in eastern Ukraine are at direct risk of destruction due to military activities (Matsala *et al.,* 2025).

The September 2024 fire in the Vyshedubechanska community affected forests were primarily dry pine and mixed deciduous forests, which are highly susceptible to fire propagation due to accumulated dry biomass. Damage to these forest types leads not only to the loss of tree cover but also to the destruction of understory species, including shrubs (e.g., Corylus avellana, Euonymus europaeus) and various herbaceous plants with ecological and soil-stabilizing roles. Moreover, military activities and explosions have led to secondary succession and invasive species encroachment, altering the composition of native flora. Satellite-based assessments using GIS and Remote Sensing (RS) technologies (EcoZagroza, 2025; Klerk *et al.,* 2022) confirm significant changes in vegetation cover and chlorophyll activity in the affected zones. In recent years, multi-source data fusion methods — combining remote sensing, ecological indices, and spatial modelling — have proven to enhance the accuracy of environmental vulnerability assessments in conflict zones (Gong *et al.,* 2025). The integrated analysis helps trace the intensity of military damage and the scale of ecosystem degradation. In regions like Donetsk and Luhansk, wartime fires have destroyed steppe vegetation, including endangered species listed in the Red Book of Ukraine, such as *Stipa capillata* and *Adonis vernalis*.

Inclusion of species-specific data and habitat types is essential not only for ecological monitoring but also for strengthening forensic documentation of environmental damage. These records provide irrefutable evidence for court proceedings and contribute to post-conflict restoration planning. Table 3 presents the calculation of the mass of unorganized emissions of various pollutants (MoUE) into the atmosphere due to a forest fire on a 1.25-hectare area. Each pollutant's emission mass was derived by multiplying the specific emission factor. qi (in tons per hectare) by the area of fire S.

$$\text{MoUE} = qi \times S$$

The data show that carbon dioxide (CO_2) has the highest emission value at 891 tons, which is expected due to the complete combustion of biomass, releasing large amounts of CO_2. Particulate matter (PM10 + PM2.5) follows with 6.75 tons, highlighting the severe air pollution and respiratory health risks caused by the fire. Other significant emissions include carbon monoxide (CO) at 3.75 tons and non-methane volatile organic compounds (NMVOC) at 0.375 tons, both of which contribute to atmospheric toxicity and greenhouse effects. Trace but highly hazardous substances like lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and benzo(a)pyrene were also detected in minute quantities. Despite their low mass, their high toxicity and bioaccumulation potential necessitate their inclusion in environmental damage assessments.

Table 3: Calculation of MoUE of unorganised emissions of pollutants or mixtures of such substances into the atmospheric air due to the burning of a forest area of 1.25 hectares

Name of Polluting Substances		*Indicators*		
		Qi	*S*	*MoUE*
		Coefficient for Forest Fires and Other Plantations, t/Ha	Fire Area, Ha	MoUE t.
NOx	Nitrogen Dioxide	0.1	1.25	0.125
NH_3	Ammonia	0.02		0.025
SOx	Sulfur Dioxide	0.02		0.025
CO_2	Carbon Dioxide	712.8		891
CO	Carbon Monoxide	3		3.75
NMVOC	NMVOC	0.3		0.375
PM10 + PM2.5 (Soot)	Particulate Matter	5.4		6.75
Pb	Lead and Its Inorganic Compounds (in terms of lead)	0.000097		0.00012125
Cd	Cadmium Oxide (in terms of cadmium)	0.000008		0.00001
Hg	Mercury Oxide (in terms of mercury)	0.000007		0.00000875
As	Arsenic. Inorganic Compounds (in terms of arsenic)	0.000044		0.000055
Cr	Hexavalent Chromium (in terms of chromium trioxide)	0.000042		0.0000525
Cu	Copper Oxide (in terms of copper)	0.000099		0.00012375
Ni	Nickel Oxide (in terms of nickel)	0.000067		0.00008375

Se	Selenium Dioxide (in terms of selenium)	0.000006		0.0000075
Zn	Zinc Oxide (in terms of zinc)	0.00085		0.0010625
Benzo(a)pyrene	Benzo(a)pyrene	0.000005		0.00000625

Table 5 applies the comprehensive formula introduced earlier in the article to calculate the monetary value of damages (AoD) caused by each pollutant. The following formula is used:

$$\mathrm{AoD} = \mathrm{MoUE} \times \mathrm{TR} \times \mathrm{HC} \times \mathrm{CI} \times \mathrm{CSE} \times \mathrm{CNE}$$

The cumulative result is a quantified total damage of UAH 2,076,344.26, equivalent to approximately USD 50,375.06. This substantial value underscores the grave ecological cost of a single military-induced fire. The dominant contributors to the overall damage include:

- CO_2: UAH 1,924,560 — reflecting its massive emission volume.
- PM_{10} + $PM_{2.5}$: UAH 70,705.71 — due to both quantity and high hazard class.
- Carbon monoxide (CO) and NOx also contribute meaningfully due to their prevalence and toxicity.

Despite their small mass, pollutants like benzo(a)pyrene, chromium, and mercury show high damage values because of extreme toxicity and elevated eco-tax rates, reinforcing the need for their inclusion in forensic reports. These calculations demonstrate that combining volume-based and hazard-based assessment provides a balanced and robust model for environmental forensic evaluation. The table supports court-admissible expert conclusions and guides remediation policy by highlighting pollutants with both ecological and financial significance.

Table 4: Visual summary of the damage calculation formula:

Symbol	*Component Name*	*Description*
AoD	Amount of Damage	Total environmental damage expressed in national currency (UAH)
MoUE	Mass of Unorganised Emissions	Total mass of pollutants or pollutant mixtures released into the air (in metric tons)
TR	Tax Rate	Eco-tax rate per ton of pollutant according to the Tax Code of Ukraine
HC	Hazard Class Coefficient	Coefficient based on the toxic class of the emitted substance (ranging from 1 to 5)
CI	Impact Duration Coefficient	Reflects how long the pollution event lasted (short-term, prolonged, or unknown duration)
CSE	Scale Coefficient	Evaluates the magnitude of the event based on the volume (tons) or area (hectares) affected
CNE	Nature of Event Coefficient	Represents the type of event (e.g., emergency, technogenic disaster, warfare)

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Table 5: Calculation of total damage caused by unorganized emissions of pollutants or pollutant mixtures into the atmosphere resulting from aviation missile debris falling on September 30, 2024, Forest (Kyiv Region, Ukraine)

Name of Polluting Substances		*Formula Indicators*						
		MoUE	*TR*	*HC*	*CI*	*CSE*	*CNE*	*AoD*
		Emission Mass, t	*Eco-Tax Amount, UAH/ton*	*Hazard Coefficient of Polluting Substances*	*Environmental Impact Coefficient*	*Event Scale Coefficient*	*Event Origin Nature Coefficient*	*Damage Amount, UAH*
NOX	Nitrogen Dioxide	0.125	2574.43	3	3	1.2	10	34 754.80
NH3	Ammonia	0.025	482.84	2				869.11
SOx	Sulfur Dioxide	0.025	2574.43	3				6 950.96
CO2	Carbon Dioxide	891	30	2				1 924 560
CO	Carbon Monoxide	3.75	96.99	2				26 187.3
NMVOC	NMVOC (Non-Methane Volatile Organic Compounds)	0.375	145.5	2				3 928.5
PM10 + PM2.5	Particulate Matter (Dust + Soot)	6.75	96.99	3				70 705.71
Pb	Lead and Its Inorganic Compounds (in terms of lead)	0.00012125	109127.84	5				2 381.72
Cd	Cadmium Oxide (in terms of cadmium)	0.00001	20376.23	5				36.68
Hg	Mercury Oxide (in terms of mercury)	0.00000875	109127.84	5				171.88
As	Arsenic. Inorganic Compounds (in terms of arsenic)	0.000055	4216.92	4				33.40
Cr	Hexavalent Chromium	0.0000525	69113.38	5				653.12

Name of Polluting Substances		*Formula Indicators*						
		MoUE	*TR*	*HC*	*CI*	*CSE*	*CNE*	*AoD*
		Emission Mass, t	*Eco-Tax Amount, UAH/ton*	*Hazard Coefficient of Pollutin g Substan ces*	*Environme ntal Impact Coefficient*	*Event Scale Coeffici ent*	*Event Origin Nature Coeffici ent*	*Damag e Amount , UAH*
	(in terms of chromium trioxide)							
Cu	Copper Oxide (in terms of copper)	0.000123 75	4216.92	4				75.15
Ni	Nickel Oxide (in terms of nickel)	0.000083 75	103816.6 2	4				1 252.0 3
Se	Selenium Dioxide (in terms of selenium)	0.000007 5	18413.24	5				24.86
Zn	Zinc Oxide (in terms of zinc)	0.001062 5	628.32	3				72.10
Benzo(a)pyr ene	Benzo(a)pyr ene	0.000006 25	3277278. 63	5				3 686.9 4
AoD			Total Damage Amount			2 076 344.26 UAH		

Once the mass emissions of pollutants or their mixtures into the atmosphere are calculated, the extent of the damage can be determined using the main formula (1). The results are illustrated in Table 5. Therefore, using the formula, we determined that the total amount of damage due to unorganised emissions of pollutants or their mixtures into the atmosphere resulting from a forest fire covering an area of 1,25 hectares following military actions amounts to UAH 1,378,637.59 for the state of Ukraine. As of September 30, 2024, according to the exchange rate of the National Bank of Ukraine, 2,076,344.26 UAH amounted to 50,375.06 USD.

According to Shevchuk, Zatenatskyi and Matulienė (2024), forensic expertise remains a primary investigative tool in obtaining evidence during investigations of ecocide under armed conflict conditions. Our research indicates that forensic expertise is crucial for calculating the scale of environmental damage and damage to plant species resulting from armed conflicts. Specifically, forensic expertise can assess: the extent of environmental damage to ecosystems and plant life resulting from military operations and/or the use of military equipment and weaponry; the scale of damages from environmental pollution and destruction or damage to plant species; damage from unorganised emissions of pollutants or pollutant mixtures into the atmosphere caused by military operations; damage resulting from contamination and pollution of land

resources due to military actions; damage caused to forests due to the destruction or damage to trees and other forest vegetation from military operations; damage inflicted upon forests due to destruction or damage to trees and other forest vegetation resulting from military activities; damage to protected natural territories due to military actions.

Krainov and Sabadash (2024) recommended:

To restore and maintain ecosystems, it is recommended to establish and expand protected areas such as national parks, nature reserves, and sanctuaries following the cessation of armed conflict and the reintegration of annexed territories. A post-war ecosystem recovery strategy should include:

1. Reclamation of damaged and contaminated lands;
2. Development and protection of new plant varieties, securing intellectual property rights (e.g., plant variety certificates under UPOV Convention or national patent law) for their use as cover crops and green manure to rehabilitate damaged soils.
3. Restoration of soil fertility and integrity through recultivation measures, fertilizer application, and planting resilient plant varieties. In this context, recent studies have confirmed that biosorption technologies offer an ecologically safe and economically viable solution for the remediation of war-contaminated soils in Ukraine (Skvortsova *et al.,* 2025).

Currently, land reclamation is challenging during active military conflict. Nonetheless, measures aimed at preserving and restoring soil fertility and integrity are crucial even during ongoing conflicts, especially in agricultural areas affected by shelling and missile strikes. Implementing timely reclamation measures, including the use of cover crops and resilient plant varieties, is essential.

In light of the findings, these recommendations merit full endorsement. In particular, the call for early and proactive implementation of soil restoration measures — even amidst ongoing conflict — is both timely and necessary. Reclamation efforts using cover crops and robust plant varieties not only mitigate immediate environmental degradation but also lay the groundwork for long-term ecological resilience and food security in war-affected agricultural regions. These proposals align closely with the forensic objectives of assessing and addressing war-induced environmental damage, offering a clear pathway toward sustainable recovery.

Discussion

The results of this study confirm the importance of forensic expertise as a scientific and procedural instrument for assessing environmental damage caused by armed conflicts. The use of a quantitative methodology to determine the scale of damage resulting from unorganized pollutant emissions presents a novel approach to evaluating environmental harm, especially in cases where direct material damage to flora and ecosystems occurs as a result of military actions. Recent publications (Khrushch *et al.,* 2023; Yaremak *et al.,* 2024) have highlighted the environmental consequences of Russia's war in Ukraine, particularly through the lens of ecocide, legal mechanisms, and the destruction of forest resources. This forensic approach bridges a crucial gap in international environmental

justice, where the environmental consequences of war are often under-investigated or underestimated. As highlighted by Shevchuk, Zatenatskyi and Matulienė (2024), the existing international legal system still lacks robust tools for systematically assessing and prosecuting environmental crimes. The formula developed in this study addresses this need by offering an objective, replicable, and legally grounded method for damage estimation.

Furthermore, the proposed model allows for adaptation to different ecological scenarios, including forest fires, soil contamination, and atmospheric pollution, caused by military operations. Given the scale of ecological harm inflicted upon Ukraine by the Russian Federation since 2022, the demand for a standardized and verifiable damage assessment tool is unprecedented. The case study of missile debris-induced forest fires in the Kyiv region provided empirical validation of the formula's utility in real-world forensic contexts. Another significant issue is the legal admissibility of environmental data. Traditional ecological assessments, although scientifically valid, often lack the procedural rigor required for courtroom use. Forensic expertise, by contrast, adheres to strict legal standards, ensuring that findings are admissible in both national and international criminal proceedings. This is particularly relevant for the International Criminal Court (ICC), which may consider charges of environmental war crimes or ecocide in future cases involving Russian military aggression against Ukraine.

The absence of a unified forensic methodology creates challenges in court proceedings, as prosecutors and judges may struggle to interpret and trust divergent expert reports. By contrast, a validated formula such as the one proposed in this study, grounded in national standards and adapted to forensic needs, can significantly increase the reliability and persuasiveness of environmental damage claims. War-related environmental crimes often affect multiple ecological domains simultaneously, air, soil, vegetation, and water, creating legal and scientific complexity (Pereira *et al.,* 2022).

Moreover, this study demonstrates that forensic methodology must be multidisciplinary. Effective assessment requires cooperation among legal experts, ecologists, forensic chemists, soil scientists, and statisticians. This approach aligns with recent recommendations on coordinated environmental governance in conflict zones, where Ukraine's experience is considered a model for future international strategies (Meaza *et al.,* 2024) The current case study drew on official data from forestry enterprises, national environmental inspection bodies, and military conflict monitoring centers — showcasing a model of institutional cooperation that can serve as a template for future investigations in Ukraine and other conflict-affected regions.

Table 6: Institutional Roles in Forensic Environmental Investigations of War Damage

Institution	*Role in Expertise Process*
Ministry of Environmental Protection and Natural Resources	Develops legal frameworks and methodologies for environmental assessment
State Ecological Inspection	Conducts field measurements, gathers evidence, and prepares preliminary impact evaluations
State Forest Resources Agency	Provides data on forested areas, biomass loss, and ecosystem degradation

Prosecutor General's Office	Initiates criminal proceedings and requests forensic expertise for environmental crimes
Forensic Research Institutes	Perform calculations, apply approved methodologies, and produce expert reports for legal use.
Judicial Institutions (Domestic and International)	Accept expert conclusions as evidence in war crimes and ecocide trials
NGOs / International Environmental Monitoring Bodies	Provide independent data, satellite-based assessments, and advocacy for environmental justice.

While the formula is promising, there are limitations to be addressed. For instance, data on exact fire duration and real-time pollutant emissions are often unavailable or imprecise in conflict zones. The methodology must therefore incorporate probabilistic or conservative estimations, which may affect accuracy. Additionally, long-term ecological effects, such as the slow absorption of toxins by soil and vegetation, are not immediately reflected in short-term damage assessments. These limitations must be acknowledged in forensic conclusions to maintain scientific credibility.

Finally, this article contributes to the broader discussion on codifying ecocide as a separate crime under international law. The empirical methodology presented here could support the development of legal frameworks, quantification standards, and judicial protocols for future ecocide prosecutions. Ukraine, as one of the first modern states experiencing full-scale ecological warfare, has a unique opportunity to establish legal and forensic precedents for the international community.

Recommendations

A unified forensic methodology should be adopted for assessing environmental damage resulting from armed conflicts, with a particular focus on the impact on plant objects and ecosystems. This methodology must be developed in line with international standards and adapted for use in legal proceedings. It is essential to integrate environmental damage assessment into the procedural framework of national investigative bodies to ensure that forensic reports are admissible in court and recognized internationally. To strengthen these efforts, a centralized database should be developed to track ecological war crimes. This database would include quantitative damage reports, GIS mapping of affected areas, and photographic documentation. Moreover, training for forensic experts in environmental damage assessment is crucial, encompassing techniques such as remote sensing, soil and vegetation analysis, and emissions modeling. International cooperation and data exchange should be promoted, particularly among countries that have been affected by environmental crimes. This collaboration will help build a common strategy for restoring damaged ecosystems. Finally, it is vital to support post-war ecological recovery strategies, which could include land reclamation, the planting of resilient crop varieties, and the restoration of protected natural territories. Recent research also emphasizes that rebuilding people-nature relationships and restoring ecosystem services is critical to long-term resilience and national recovery (Elbakidze *et al.,* 2025). These recommendations aim not only to strengthen Ukraine's national capacity to address

wartime ecological damages but also to contribute to the formation of a global precedent for prosecuting environmental war crimes. To calculate the environmental damages inflicted upon ecosystems using the formula currently applied in Ukraine for assessing damages caused by unorganised emissions of pollutants or their mixtures into the atmosphere resulting from military actions and/or emergencies is an effective proposition. In parallel, it is essential to develop a standardised methodology for forensic expertise aimed at quantifying environmental damages from warfare, the conclusions of which can serve as evidence in criminal proceedings at the International Criminal Court against the Russian Federation for war crimes committed in Ukraine. The proposed formula (1) for calculating environmental damages could serve as a foundational tool for developing forensic methodologies to assess damages inflicted on the natural environment and plant life, taking into consideration specific cases involving negative impacts on atmospheric air, soils, and flora.

Conclusion

Forensic expertise is one of the most reliable and effective means of collecting evidence to establish factual data in various legal conflicts, particularly in determining the extent of damage caused to plant life. Expert examinations are based on scientifically validated, practically proven, and officially approved methods and techniques, the results of which are suitable for use in both national and international judicial proceedings concerning the investigation of war crimes. The conclusions of forensic expertise constitute critical evidence in establishing accountability for environmental war crimes, the causes that determined their occurrence, and in determining compensation.

The analysis of damage to plant life resulting from the Russian–Ukrainian war shows that Ukrainian forensic methodologies, although effective, require further integration with international environmental protection standards to ensure the recognition of findings in cross-border litigation. The study also revealed the potential of applying modern technologies and approaches currently used by Ukrainian environmental specialists when examining the ecological consequences of war, such as satellite imagery, remote sensing, and GIS mapping, to improve the accuracy of damage assessment.

Based on the results, it is recommended to:

1. Develop unified national and sector-specific methodological guidelines for assessing damage to vegetation in armed conflict, harmonized with international law.
2. Introduce specialized training programs for forensic experts on environmental crimes.
3. Strengthen cooperation between state authorities, research institutions, and international organizations to ensure methodological consistency and transparency in the field of environmental security and the prevention of war-related ecological threats.
4. Establish clear legal mechanisms for calculating compensation for war-related environmental damage to vegetation.

Future research should be aimed at improving the accuracy of forensic damage assessment models, exploring the applicability of ecological modelling tools, and

conducting comparative studies of environmental consequences in different conflict zones. Strengthening the methodological basis of forensic expertise in this field will contribute to achieving environmental justice and preventing future violations of environmental and humanitarian law.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*
Conceived and designed the research or analysis	Yes	No	Yes	No	Yes
Collected the data	No	Yes	No	Yes	No
Contributed to data analysis & interpretation	Yes	No	No	No	Yes
Wrote the article/paper	No	No	Yes	Yes	No
Critical revision of the article/paper	No	Yes	No	No	No
Editing of the article/paper	No	No	Yes	No	No
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